A VIRTUAL ENVIRONMENT SYSTEM FOR THE STUDY OF HUMAN ARM TREMOR

by

Bernard Dov Adelstein

B.Eng. in Mechanical Engineering, McGill University (1978)

S.M. in Mechanical Engineering, M.I.T. (1981)

SUBMITTED TO THE DEPARTMENT OF
MECHANICAL ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1989

Signature of Author ______________________________
Department of Mechanical Engineering
May 19, 1989

Certified by ______________________________
Michael J. Rosen
Thesis Supervisor

Accepted by ______________________________
Ain A. Sonin
Chairman, Departmental Committee on Graduate Studies

A VIRTUAL ENVIRONMENT SYSTEM FOR THE STUDY OF HUMAN ARM TREMOR

by

Bernard Dov Adelstein

B.Eng. in Mechanical Engineering, McGill University (1978)

S.M. in Mechanical Engineering, M.I.T. (1981)

SUBMITTED TO THE DEPARTMENT OF
MECHANICAL ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1989

Signature of Author ______________________
Department of Mechanical Engineering
May 19, 1989

Certified by ______________________
Michael J. Rosen
Thesis Supervisor

Accepted by ______________________
Ain A. Sonin
Chairman, Departmental Committee on Graduate Studies

A VIRTUAL ENVIRONMENT SYSTEM FOR THE STUDY OF HUMAN ARM TREMOR

by

Bernard Dov Adelstein

Submitted to the Department of Mechanical Engineering on May 19, 1989 in partial fulfillment of the requirements for the Degree of Doctor of Philosophy

ABSTRACT

Understanding the causes of different tremor types can provide insight into the function of the normal and pathological neuromuscular system, and is essential for definitive diagnosis and effective treatment. The most frequently employed experimental technique to distinguish among hypothesized tremogenic mechanisms has been observation of the influence of peripheral mechanical loading on oscillation characteristics. To date, research has focused on the mechanisms of single joint tremors occurring primarily during the maintenance of static postures.

This thesis describes the design and implementation of a virtual environment system for the study of whole arm (two joint) tremor during voluntary movement. The system consists of a manual interface to apply controlled two degree of freedom mechanical loads and a video display for the presentation of volitional arm tasks.

The manual interface for the virtual environment is in essence a backdriveable electromechanical manipulator. It is based on a novel spherical closed chain configuration designed to exceed the bandwidth requirements for tremor research by minimizing the geometric computation needed for load simulation. The performance of the system was tested by simulation of mechanical load fields and physical objects such as hard walls and detents in which controller update rates of 1 kHz and higher were achieved using an LSI-11/23 microcomputer.

The applicability of the system to the study of whole arm tremor was demonstrated in preliminary experiments with a tremor disabled subject. A proposal for future two joint tremor experiments is also described.

Thesis Supervisor: Dr. Michael J. Rosen
Title: Principal Research Scientist

MEMBERS OF THE THESIS COMMITTEE

Dr. Michael J. Rosen (Chairman)
Principal Research Scientist
Department of Mechanical Engineering

Dr. Neville Hogan
Professor
Department of Mechanical Engineering

Dr. Robert W. Mann
Whitaker Professor of Biomedical Engineering
Department of Mechanical Engineering

Dr. Robert R. Young
Professor of Neurology
Harvard Medical School

Acknowledgements

The process of getting an education and completing a dissertation is not something one does alone. Many fine people helped in my pursuit and attainment of these goals. It is indeed a great pleasure to acknowledge their contributions here.

To Mike Rosen, supervisor of both my M.I.T. theses, my academic advisor, and good friend, I want to express my heartfelt thanks for everything. He has been a willing supporter—moral (always) and financial (nearly always)—for over a decade. His unfettering management style enabled me to develop both as an engineer and scientist, at my own rate, and in the direction of my own choosing (or at least, Mike had let me feel that most of the choices were really mine). Most importantly, he provided me with the opportunity to learn mechanical design by actually doing it rather than just talking about it.

I also wish to extend my thanks to Robert Young, Robert Mann, and Neville Hogan, the other members of my doctoral committee. They gave of their time to attend the meetings and read drafts of this document, and, through their comments and insight, helped shape the thesis' final form.

I am very grateful to Norm Berube, jack of nearly all trades. He took my machine drawings, often suggesting improvements, and formed them into the aluminum, Delrin, and Lexan parts that became the manipulandum described in these pages.

Many of my fellow students have been capable instructors and accomplices over the years. I deeply appreciate each of their contributions and hope that I have been able to return to them as much as they have collectively given me.

Crispin Miller came back three days after a lab seminar given when this work was in its seminal stage, knocked on my window, and beseeched me to take away a sheaf of paper and a cardboard model that had been plaguing him most of that weekend. His musings on those pages solidified the concept that became the manipulandum.

Will Durfee, whether he realizes it or not, abetted in my education in electronics; much of what I know started by watching him work. My keeping a written record of all of my thesis work stems from an effort to emulate Will's appearance of always having everything in order.

Bill Murray and Cary Abul-Haj further strengthened my understanding of digital electronics and the innards of PDP-11 computers. Bill, Ed Colgate, Mike Murphy and I have whiled away innumerable hours pondering system dynamics, modelling, kinematics, life-in-general, and academia. They taught me a lot and gave much to think about.

Ivan Baiges permitted me to use the skeleton of his thesis' whole-arm orthosis for a validation study of my apparatus. Scott Maxwell's universal subject testing chair served as the anchor and reference frame for that study. Scott's previous experience also led to the force transducer "decoupler" described herein. Janet Zahradnik donated "starter"

code which made learning and programming the Amiga computer much less painful.

In addition, Keita Ito, John Mansfield, Pete Mansfield, Greg Brown, Pat Lord, Eric Lanzendorf, and Dawei Qi provided the tangibles (computer maintenance expertise and the like) that keep a place like the Newman Lab functioning, as well as the intangibles (humor and camaraderie) that make it more than just a place in which to work.

My parents have never let their confidence in me flag. They gave me a caring home in which to grow, with as close to complete freedom as a kid could hope for; encouraged learning; and never deterred my curiosity. I offer them my undying gratitude.

Laura Demsetz, my wife and best friend, with her love, enabled me to endure the years at M.I.T. She has a hand in this thesis (literally)—I thank her for technical consultation, rendering figures on the Mac, and for unflichingly always being there when I needed it most.

Dov Adelstein

This work was performed in the Evelyn E. and Eric P. Newman Laboratory for Biomechanics and Human Rehabilitation. It was funded in part by grants from NINCDS, Public Health Service, Department of Health and Human Services (5R01-NS17610-03); NIDRR, Department of Education (G008300074); the Burke Rehabilitation Center, White Plains, NY; and a fellowship from the Sherman Fairchild Foundation.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The ability to observe the interaction of human beings with external mechanical environments under well controlled experimental conditions provides a valuable research method for the study of many aspects of human motor control, from intrinsic biomechanical and sensorimotor hardware up to commanded behavior that originates at cognitive levels. A testing facility that incorporates the means for imposing well characterized experimental conditions—both the commanded state of activity in the human and the effective mechanical environment with which the limb must interact—can serve as a tool to investigate not only properties internal to the human, but also the combined dynamics of the human-environment system and the nature of the sensory and mechanical coupling between the human and the external environment.

In devising a testbed for experimental studies of manual control and sensorimotor physiology, it is essential to note that during the performance of normal daily tasks, mechanical coupling between the human and the environment, in addition to altering the overall system dynamics, generates a rich array of sensory information. Both the intensity and texture of contact with the surroundings (tactile sensation) and the body's internal sense of its own kinematics and force generation (proprioception) present stimuli to cognitive perception and are vital for active neuromuscular regulation of dynamic interaction with the environment. The other senses, especially vision, may also play a key role in the skillful performance of many manual activities. Of necessity, a testbed

for research into human arm dynamics and manual control must first include the means to measure the combined human-environment kinematics and dynamics. Second, as mentioned above, the testbed must enable the experimenter to dictate both the volitional activity desired of the human subject, as well as the dynamics of the environment to which the subject is coupled. One approach to accomplishing the second task is to *simulate* the physical characteristics of the elements that the human acts upon.

Employing *physical simulation* offers several advantages over gathering observations during the performance of *real* tasks with a *real* system.[1] As with simulation in any field of endeavor (*e.g.*, econometric modelling, wind tunnel testing, situation room role playing in military training, *etc.*), physical simulation is driven by a *model* of the real system. A valid model strips away unnecessary detail, facilitating the observation of essential features that would otherwise be obscured by the complexity of the real system. Not only is the extraction of data often simplified, but a useful model can easily be revised. In contrast, revising the real system may be prohibitively expensive or physically unrealizable. Simulation may in fact be essential for the study of certain events because potential outcomes of the real situation or process are too hazardous. The benefits of simulation can be distilled to a single notion—the experimenter is given precise convenient control over essential experimental conditions. The insight developed by simulation may assist in predicting the outcome of real processes, aid in the design of new ones, or train users how to productively employ existing ones.

Any simulation that is computer based executes sets of mathematical equations that model key aspects of a real system and is intended to provide insight by generating useable information on how that system responds to sets of exogenous inputs. When dealing with *interactive* computer based simulations, the issue of how the human is coupled to the system arises. Most interactive computer simulations only include the human in the loop in a limited fashion. Typically, information transfer in interactive

[1]The term "physical simulation" connotes that the simulation has physical reality, *i.e.* the elements with which the human interacts have the properties of real physical entities. It is a simulation in that the characteristics of many different physical elements can be emulated.

simulations is restricted to the human operator observing graphical or numerical outflow from the simulation on a terminal monitor, and responding to the conditions unfolding in the computer model through a keyboard, a joystick, or a mouse. In that type of situation, the actual physical dynamics of human-machine interaction do not enter into consideration.

Computer based simulations which attempt to model the human as an integral component of the system under investigation pose another set of challenges. These challenges, many of them as yet unresolved, deal with generating accurate quantitative representations that capture essential aspects of complex skeletal, muscle, and nerve properties, in addition to cognitive behavior. A more successful alternative may be studies of human-environment interaction in which the actual human operator, rather than a model of the human, is interfaced to the simulation of the physical system.

A computer controlled interface for interactive simulation that couples the human to simulated physical elements must stimulate the internal self-sense of dynamics in the limb (*i.e.*, proprioception). The objective is, at minimum, to impose the desired dynamics on the human through the computer-controlled physical interface *and*, through visual presentation, to define the task that the human operator should execute. The ultimate goal is to evoke in the human operator the sense of "really being there" in a virtual space with simulated objects, performing virtual tasks. Because of the versatility of a simulation that is computer generated, artificial physical components are fabricated by simply including segments of computer code. The fidelity of these computer emulated objects depends both on an understanding of the detail and accuracy necessary for subjectively succesful simulation, and on choosing simulation hardware capable of delivering the desired performance.

1.1 Thesis Objective and Scope

The goal of this thesis is the design and implementation of a virtual environment system that simulates the mechanical characteristics of physical objects for human manual ex-

periments. The development of this system has been geared toward the investigation of a specific component of human motor activity: tremor.

This simulation system is intended to physically interact with the human operator (*i.e.*, the experimental subject) through the application of mechanical loads that simulate physical objects, and thus modify the dynamics of the operator's arm. The load simulation capabilities of the system allow the "feel" of a range of different objects and environments to be emulated. The system also gives the operator a visual representation of the virtual task he/she is performing. In addition, as a laboratory-based research tool, this system acquires and stores records of relevant performance variables for the subsequent analysis of operator performance.

While the design specifications for this testbed were directed at meeting requirements for the study of a specific component of human manual output, the applicability of the resultant system, as will be demonstrated, is more global.

1.2 Organization of the Thesis

A description of what tremor is, the motivation for its study, and the rationale for employing a physical environment simulation system as a tool for tremor research are topics of the remainder of this chapter. The concept of physical emulation of mechanical devices and systems is developed further in Chapter 2, with examples of hardware systems from a number of areas drawn upon for illustration.

Chapter 3 defines the issues relevant to the design of the arm loading and visual task presentation system. The desired performance characteristics and constraints imposed on the final system, and the strengths and weaknesses of other related devices are reviewed here.

The next two chapters span the implementation and performance of the hardware designed and built for the virtual environment system. Chapter 4 is concerned with the design of the arm loader hardware. This chapter includes the description of a new coupling mechanism that joins fixed-base electromechanical actuators to the mechanical

interface of the device with the human user, the selection of sensors and electromechanical actuators, and the measured performance of the passive (uncontrolled) machine. Chapter 5 treats the computer supervision and control of the entire system, including the implementation and performance of the impedance controller used to simulate the mechanical characteristics of a range of physical environments, the logic and hardware that maintain safe operation of the loader, and the video display. An experimental protocol for the study of whole arm tremor, using the virtual environment system, is proposed in Chapter 6. The results of some preliminary experiments with a tremor-disabled subject and the implications of these tests for the design of the experimental protocol are also discussed. The contributions of this thesis are summarized and recommendations for further work are made in Chapter 7.

1.3 Tremor

1.3.1 Normal and Pathological Tremors

Tremors are involuntary oscillations that are superimposed upon the volitional force or kinematic output of any limb segment or body part. This rhythmic mechanical activity is seen in *all* healthy people as well as in individuals with neurological disorders. Tremor can be present when the limb is supported externally such that its related musculature is at rest; when the related musculature is required to produce constant levels of force during maintenance of a limb's posture against gravity; and when dynamic force trajectories are executed by the muscles, as occurs during purposeful movement.

Because tremor is rhythmic in nature, it can be described in terms of its frequency content and the amplitude at these frequencies. It is based on these measurable characteristics that the distinction between normal ("physiological") and pathological tremors is drawn. Physiological tremor, which is present in able-bodied individuals, under most circumstances ranges in frequency from 8 to 12 Hz, and is small in amplitude, requiring special instrumentation to demonstrate its presence. Pathological tremor magnitudes are, at minimum, visually obvious without special instrumentation, and can be severe

enough to obscure concurrent voluntary motor activity in the afflicted limb to the point of functional impairment. Pathological tremor frequencies can be as low as 1.5 Hz and range up to the frequencies of normal tremor [68].

Pathological tremor may arise from degenerative neurological conditions including multiple sclerosis, Parkinson's disease, and various hereditary ataxias; toxic factors including chronic alcohol ingestion, and exposure to lithium salts; or sudden incidents such as stroke and head injury. In some individuals with these conditions, tremor may be one of many disabilities present. In others, tremor may be the only manifestation of neurological abnormality.

1.3.2 Tremogenic Mechanisms

As a result of extensive clinical observation, human and animal experimentation, and analytic modelling studies over the course of the past four decades, tremogenic (tremor causing) mechanism hypotheses have been formulated to explain the sources of particular oscillations and the factors that shape their characteristics. These hypotheses, which have their basis in the growing understanding of the roles of individual sensorimotor components and their interconnections in human movement control, have been applied to both pathological and normal tremors. Hypothesized tremogenic mechanism models have been grouped into the following three broad classes: biomechanical resonances, reflex loop instabilties, and central oscillators [133].

The biomechanical resonance model presupposes that the combined limb and external load, as depicted in Figure 1.1, have the characteristics of an underdamped second order system. In this model, the oscillatory frequency of displacement tremor is tuned by the equivalent joint stiffness and the combined limb-load inertia. The force (torque) input to the equivalent system need not be tuned at all; it can result from the broad band noise of random motor unit firing in the related musculature [136, 116].

The reflex loop mechanism, as depicted in Figure 1.2, takes the finite conduction delays inherent in neuroelectrochemical transmission into consideration—both in the de-

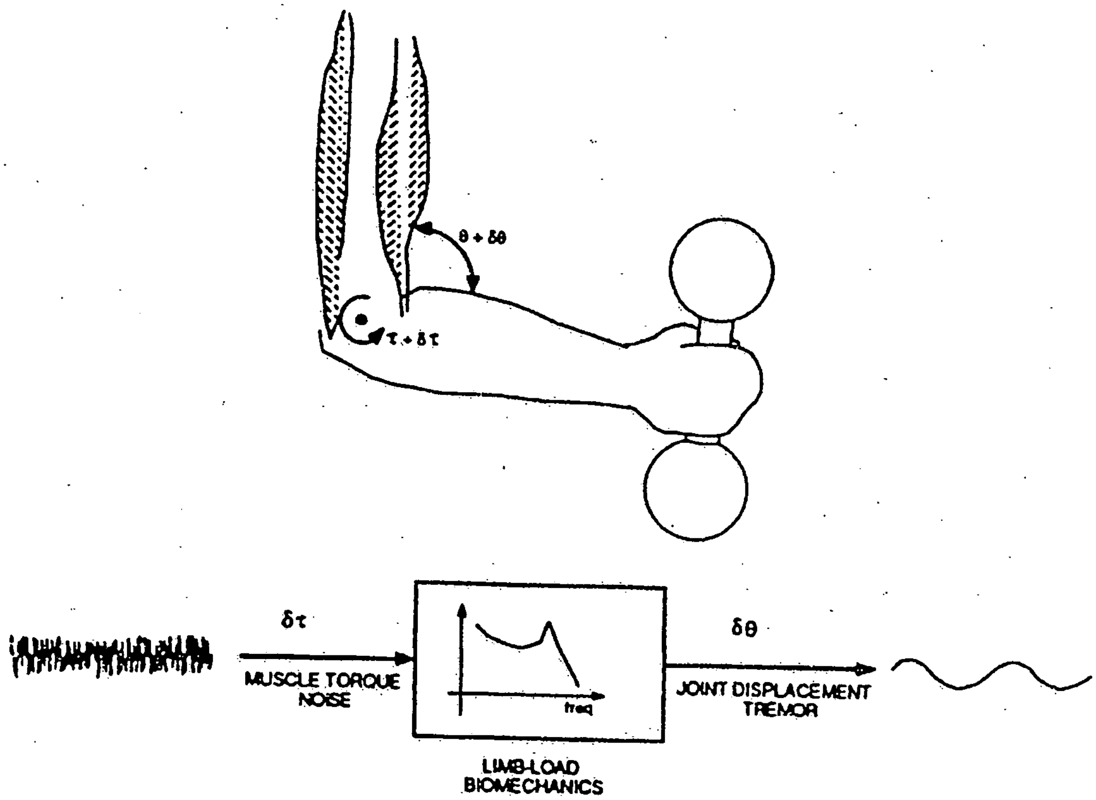

Figure 1.1: Biomechanical resonance tremor mechanism model. The mechanical load consisting of the combined forearm and external mass inertias and the equivalent muscle stiffness about the elbow are driven by broad band torque fluctuations $\delta\tau$ due to the random firing of individual motor units. The resulting narrowly tuned displacement output is rhythmic forearm flexion-extension $\delta\theta$, *i.e.*, tremor.

scending (efferent) neural command channels to the muscle and within the muscle itself, where neural signals are transformed into mechanical action, and in the ascending (afferent) pathways that carry signals back up from the rich array of internal muscle force and strain transducers. If the effective gain margin of the reflex loops from these transducers back to the muscle actuators is insufficient, sustained neural oscillations can develop at the phase crossover frequency, leading to rhythmic tremor in the mechanical output of the muscles [91].

The central oscillator hypothesis proposes that oscillatory sources in the central nervous system—unaffected by short-term peripheral feedback from muscle or other internal transducers—simply entrain groups of spinal neurons to send synchronous drive signals to the muscles, resulting in tremor. Sites postulated for central oscillators include brain areas responsible for the coordination of movement [87] and regions in the spinal cord [52], as schematized in Figure 1.3.

There is no reason to expect that any one of these mechanisms exist independently in a particular limb or muscle group under investigation. Several different oscillations may occur simultaneously in the same limb, each governed by a different mechanism [8, 9, 50, 78]. (See Figure 1.4.) It is also possible that two or three of the mechanisms may coalesce to produce a solitary oscillation [134]. The relative weighting of each tremogenic mechanism contribution depends on many factors, including pathology, emotional state, metabolic factors, and the type of concomitant voluntary activity in the muscle group. Also, the three mechanism hypotheses represented here need not be linear phenomena. Some analytic tremogenic models have incorporated nonlinear features, for instance, in considering muscle activation properties and reflex loop characteristics [132, 153].

These three general mechanism classes were elucidated here in a very brief format with the expressed intent of summarizing the hypotheses, rather than reviewing the evidence for each. It is important to note that these mechanism hypotheses were developed to explain tremors which arise due to the activity of either a single muscle group (agonist) or muscle group pairs (agonist and antagonist) that act in a single kinematic degree of

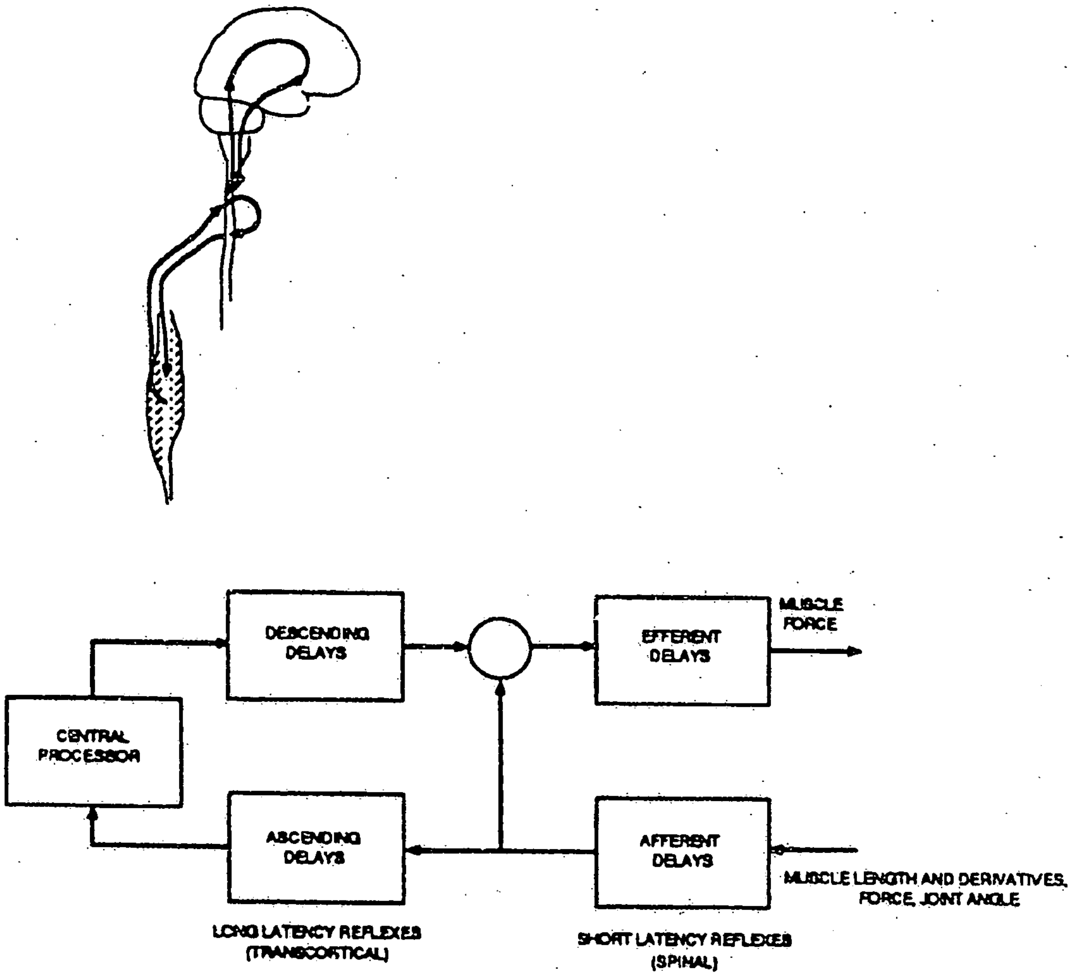

Figure 1.2: Reflex loop oscillator tremor mechanism model. Delays in muscle activation contraction and neural transmissions in the spinal reflex arc (spinal cord efferent-muscle-muscle sensor afferents) and in longer latency pathways (brain-descending spinal cord-spinal cord efferent-muscle-muscle sensor afferent-ascending spinal cord-brain) may compromise the stability margin of closed feedback loops, leading to sustained involuntary mechanical oscillations.

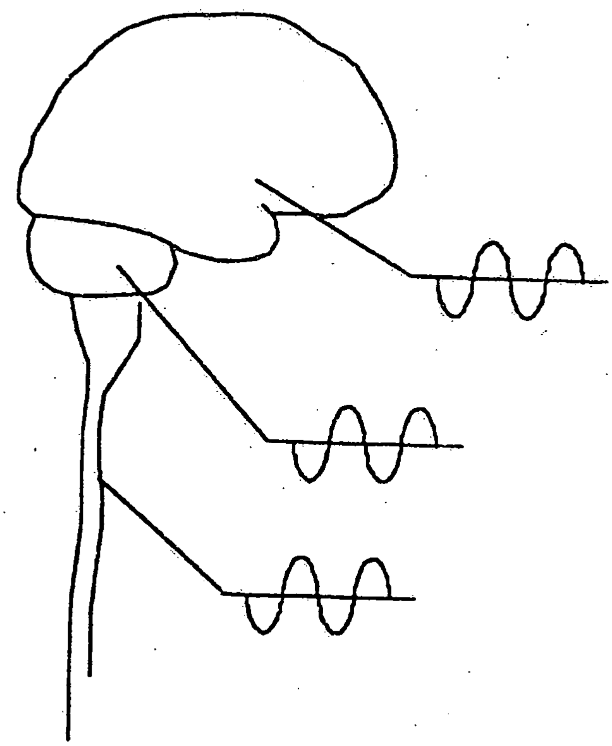

Figure 1.3: Central oscillator tremor mechanism model. Proposed origins of descending involuntary oscillatory commands to the musculature include sites in the motor cortex, cerebellum and related areas, and at the segmental level in the spinal cord.

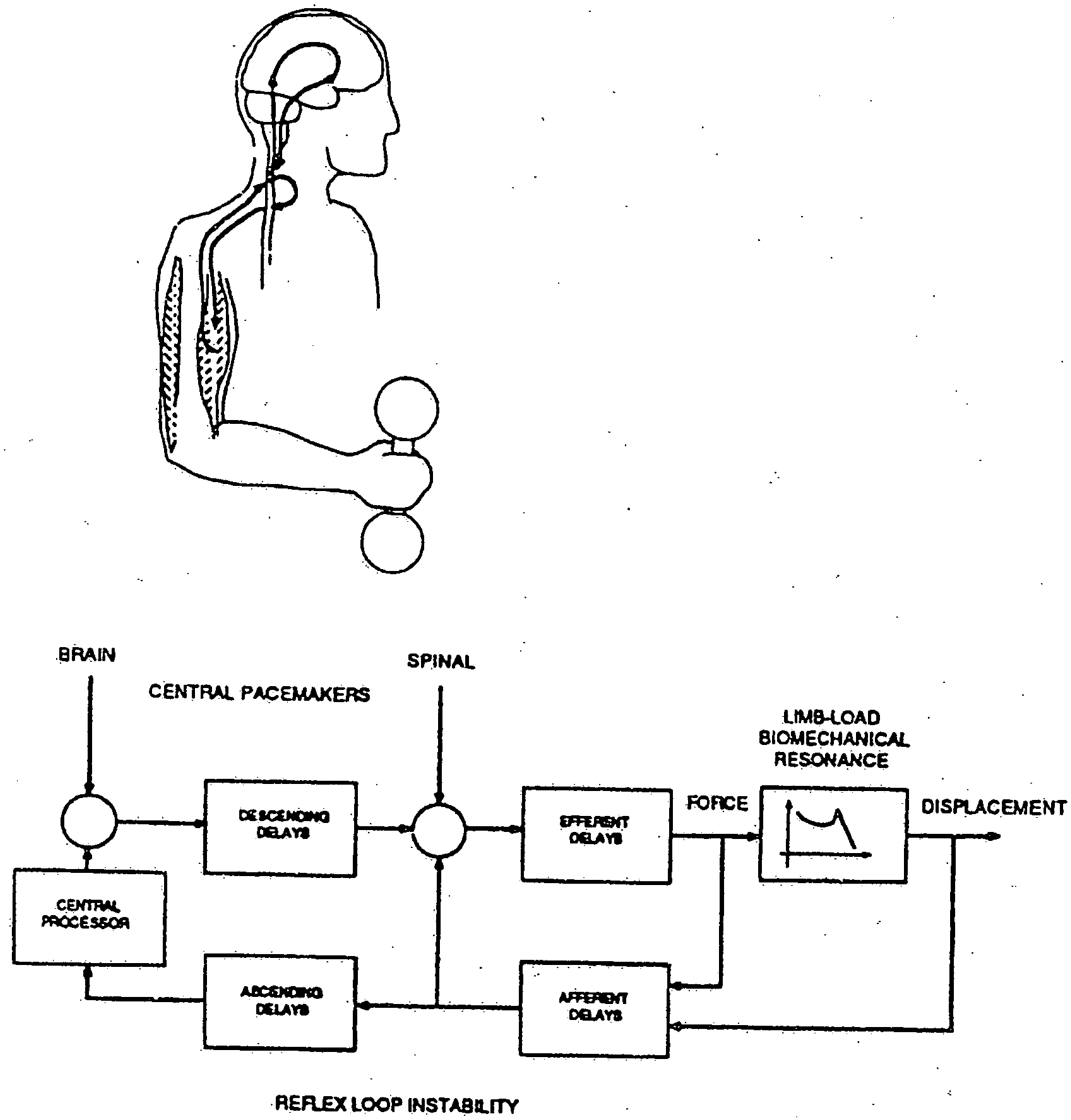

Figure 1.4: Combined biomechanical resonance-reflex loop-central source oscillator tremogenic mechanisms. See text for details.

freedom about a single joint. To date, models that consider potential tremor coupling, either mechanical or neuromuscular, between many groups of muscles in a multi degree of freedom limb have not been reported.

1.3.3 Tremor Measurement

Accurate measurement enables the mechanical and electrophysiological attributes of different tremors to be quantified, both for the experimental investigation of tremor generating mechanisms and for clinical evaluation.

The principle methods that have been employed for electronic detection of tremor *motion* include potentiometeric joint angle measurement (*e.g.*, references [6, 36, 146]), and uniaxial (*e.g.*, references [30, 78, 96, 104, 136]) and triaxial accelerometry [64, 128]. Because of the construction of rotary potentiometers, goniometric (joint angle) sensors are best suited for situations where the limb segments are constrained to single degree of freedom motion by anatomy or external apparatus. Accelerometers, on the other hand, require careful alignment if their readings are to be interpreted in terms of anatomical coordinates.

Other non-contacting arm tremor motion measurement techniques and apparatus have also been demonstrated. These range from the simplest—and least satisfactory—technique in which planar time-lapse photographs of single limb-mounted luminous markers are deciphered [73, 103], to a more elegant and accurate planar two degree of freedom capacitive transducer [86], and a three dimensional position detecting optoelectronic system [4]. To date, multi degree of freedom kinematic tremor measurements have not been decomposed into joint angle components.

Uniaxial [63, 91, 97, 139] and biaxial [117] tremor *force* measurements for quasi-isometric situations have also been reported. The term "quasi-isometric" is used here because only the contact point of the limb with the stiff fixed-base transducer is truly immobile; the skeleton of the limb can be restrained only to within internal tissue compliance. Neither joint torque components nor individual muscle forces associated with

multi degree of freedom whole limb tremor have been described in the literature.

Indications of tremor-correlated muscle activity, though, can be derived from the analysis of myoelectric signals [34, 60, 97, 135, 154]. Direct neural signals corresponding to tremor transduced by the muscle spindles (internal muscle strain sense organs) have also been recorded [152]. However, because of the nature of surface and in-dwelling electrodes for myoelectric and neural activity measurements, both of these methods are best suited for isometric or near-isometric situations. Consequently, their use may be precluded when rapid and/or large amplitude pathological tremors or voluntary motion are present.

1.3.4 Voluntary Task Specification

It was noted at the begining of Section 1.3.1 that tremor can be present when the limb is at rest, holding a static posture, or executing a dynamic trajectory. Tremor classification, a first step to clinical diagnosis, is based upon the identification of which of these general levels of volitional activity elicits the most severe form of a particular tremor in an individual patient [55]. Thus, the prescription of concomitant voluntary activity is a major element in designing the protocol for a tremor mechanism study.

Investigations of tremors that are exacerbated by *dynamic* voluntary activity, either movements or forces, necessitate stimulation of the appropriate volitional motor behavior in the subject/patient. To more easily characterize this type of motor behavior, the subject should perform pursuit tracking tasks, during which the subject is presented with a moving target and is instructed to match the excursions of the target (*i.e.*, pursue the target) with a response marker driven by mechanical output from the body segment under examination. Pursuit tracking has been employed in the study of large amplitude pathological tremors in one and two dimensional tasks, both with discrete target location jumps [27, 57, 69, 117], and continuous target trajectories [9, 11, 117].

The vast majority of human tremor experiments reported in the literature (especially those concerned with tremor mechanism identification), however, have been performed

under *static* postural maintenance conditions, and as such are more applicable to the tremor present during that class of voluntary activities. In that type of experiment, the subject's objective is simply to maintain a constant force or displacement throughout the course of a test. Often, the subject in a postural maintenance test is actually provided with visual feedback, resulting in a situation that is equivalent to a visually mediated tracking task—pursuit tracking when both the target and response markers are shown [78, 82, 91, 97]; compensatory tracking when the difference (error) between the two signals is presented [12, 91].

1.3.5 Mechanical Loading

Controlled mechanical loading, in conjunction with the mechanical and electrophysiological measurement techniques described above, has been a vital research tool for the identification of general mechanism classes involved in the genesis of different pathological and normal tremor types. Mechanical limb loading studies in which the equivalent stiffness [51, 82, 97, 118, 145], viscous damping [145], and inertia [50, 78, 136, 145] were altered have been reported. Randomly timed force perturbations [51, 90, 91, 135, 142, 145] and low frequency mechanical vibration (on the order of 100 Hz or less) [45, 111] have also been employed.[2]

Examples of how tremor response to mechanical loading has been interpreted in the above cited references, in view of the tremogenic mechanism classes described in Section 1.3.2, are as follows:

- A shift in a tremor's frequency downward with augmented inertia, or upward with heightened stiffness has served to indicate biomechanical resonance as a factor in tremogenesis.

- The ability to re-entrain (phase lock) a tremor's timing in response to a force perturbation for a period longer than the die-away response of the limb biomechanics

[2] A review of mechanical loading as a tool for tremor mechanism research can be found in reference [7].

has been used to indicate the role of reflex arc activity in sustaining the oscillations.[3]

- By default, the invariance of a tremor's mechanical properties (*i.e.*, frequency, amplitude, and timing) in response to both force perturbations and changes in inertia or stiffness has been used to implicate central oscillatory sources.

1.4 A Virtual Environment System for Whole Limb Tremor Experimentation

It was pointed out in Section 1.3.2 that tremor mechanism studies have not yet been extended beyond single degree of freedom models, and in Section 1.3.3 that multi-joint tremor torques or kinematics have yet to be measured or derived. Also, mechanical loading of tremorous limbs in greater than one degree of freedom has been reported in very few instances. Among these few instances are descriptions of viscous damping interfaces [3, 120] and an investigation of the therapeutic benefit of weighted wrist cuffs [73], all directed toward rehabilitation of the tremor disabled rather than mechanism research.

By proceeding beyond single degree of freedom tremor loading and measurement, tremor models could be extended to multi-joint whole limb cases that are more representative of "activities of daily living" (ADL) situations. Some unanswered issues to be investigated include the following:

- Whether tremors present at different locations or in different degrees of freedom of the arm have independent oscillatory sources or are cross-coupled;

- If tremor oscillations are coupled, whether the nature of the coupling is purely mechanical (*i.e.*, the result of multi-segment linkage dynamics), muscular (*i.e.*, due to biarticular muscle action), or neural (*i.e.*, due to local feedback);

[3] The contribution of nonlinear mechanical properties in generating sustained oscillations is also a possibility. Elble *et al.* [51] suggested that one could distinguish between biomechanical and neural factors by first altering the limb segment's inertia and then observing whether the re-entrained oscillation occured at the new (*i.e.*, shifted) mechanically resonant frequency.

- In whole-limb cases, as for single degree of freedom tremors, which tremogenic mechanism(s) are responsible for individual oscillations and what types of voluntary motor behavior provoke them.

The benefit of resolving these and other issues is an enhanced understanding of the mechanisms that generate whole limb tremor and, in some situations, lead to disability. This understanding will help develop more accurate tremogenic models, which in turn will contribute to the design and evaluation of improved diagnostic methods, pharmacological and surgical procedures, and rehabilitation regimens. Additionally, a more complete appreciation of the role played by the neuromusculoskeletal system in generating involuntary tremor may offer insight into the organization and planning of classes of volitional activity that use much of the same "hardware."

To extend accurately controlled tremor experimentation beyond single degree of freedom situations, the virtual environment system outlined in Section 1.1 was developed. The system includes a manual interface to permit a wide range of programmable mechanical limb loading; a visual interface to present tracking tasks that enable the specification of resting, static, or dynamic levels of voluntary activity from the subject; and instrumentation for the measurement of kinematics and forces.

Chapter 2

Review of Kinesthetic Virtual Environment Systems

This chapter presents a survey of experimental systems that incorporate physical simulation in the form of controlled mechanical loading at their interface to the real world. Examples are drawn from the areas of telemanipulation, computer interfaces, actively loaded manual controllers, and the experimental neurosciences.

2.1 Terminology

The terms kinesthetic, tactile (or tactual), proprioceptive, and haptic are used, often interchangeably, to describe the sensory input that the operators of virtual environments and other force loading manual interfaces receive from such systems. This section is intended as a very brief glossary of relevant sensory terminology.

Tactile is related to the sense of touch, specifically through cutaneous receptors that are present in the skin over the body surface [46]. According to Stedman's Medical Dictionary [2], tactual input is applied to the tactile sense.

Kinesthesia is the sense of limb movement or position, arising primarily from the output of muscle spindles, the internal parallel muscle sensors that transduce muscle length change (*i.e.*, stretch) and rate of change [72]. The role of joint capsule receptors in detecting joint angle changes has also been noted [31]. Roland [119] differentiated

between *kinesthesia* to describe the "perception of change in the position of a limb due to muscular contraction" and *statognosia* for "perception of position of a limb in space" through passive externally imposed movement.

Proprioception is the internal "self sense" of limb dynamics, and includes kinesthesia plus muscle tension as sensed by Golgi tendon organs [72, 100, 119]. Proprioception describes sensation that is caused by the actions of the organism itself, while exteroception pertains to sensation that results from external inputs from the environment [31].

Haptic acccording to Werner [147], is related to the unified and coordinated activity of the tactile and kinesthesic senses, as a higher integrated function of the nervous system. The haptic sense is equivalent to "active touch" as described by Brooks [31], employed in the active, consciouc exploration of the texture and shape of objects.

The adjectives tactual and kinesthetic are typically employed to describe the sensory input that is provided to the human operator during manual interaction with a force loading interface. Thus, physical simulation systems that evoke activity in these senses have been labeled tactual, kinesthetic, or tactual/kinesthetic[1] virtual environments.

The virtual environment system designed for this thesis does not include tactual communication to the human operator in that cutaneous touch receptors are not involved, *i.e*, the user does not employ his/her fingertips or skin surface to discriminate among simulated object textures. However, because the manual interface of this system is a force loader, it does impart changing kinematics to the limb, while also necesitating active tension in muscles that work against the simulated loads. As such, the human operator depends on *proprioceptive* information to fully sense the mechanical characteristics of the physical simulation presented by the virtual environment. Even though internal muscle tension is an important contributor to the human operator's perception, the label

[1]The term "haptic" might be considered as a more compact equivalent to "tactual/kinesthetic."

"*kinesthetic* virtual environment" will be used to describe this system to conform with other work in the field.

2.2 Telemanipulation

The goal of telemanipulation is to furnish the human with the ability to manipulate objects from afar and thereby eliminate the hazards of working in hostile environments (*e.g.*, outer space or undersea) or in the handling of dangerous materials (*e.g.*, radio-isotopes or explosives). In tasks involving direct manipulation (*i.e.*, direct contact between the human and the object), the proprioceptive and tactile senses transmit information back to cognitive levels and fulfill a vital role in the identification of properties of the objects that are being handled. Especially in unfamiliar conditions, this feedback is essential to the human for evaluation of how well manual tasks are performed, and consequently for "on-line" learning so that tasks can be executed successfully. Similarly, in remote manipulation, high quality proprioceptive information is important for skillful task performance. The term "telepresence" has been used to describe the situation where full sensory information available at the remote manipulator is transferred back to the human, so that he/she has the perception of actually being at the remote site.[70, 130]. Among the desired sensory components of telepresence are "teleproprioception" and "teletouch" which would be provided by displays that reflect the forces experienced by the remote manipulator.

A convenient starting point for a brief history of remote manipulation is nuclear "hot room" work of late 1940's in which mechanical master-slave linkages originally were employed to handle radioactive materials behind shielded partitions.[2] The human operator at the "master" of such a system would experience the interaction between the "slave" and the workpiece as transmitted through the mechanical linkage. Of course, because of undesirable linkage characteristics such as friction and inertia, the fidelity of sensory perception would be degraded. Purely mechanical, passive linkages were soon

[2] A very complete history of telemanipulation can be found in reference [144].

supplanted by electromechanical and electrohydraulic devices, first with unilateral and then with bilateral master-slaves. The term unilateral indicates that the direction of information flow is from the human master to the motorized slave manipulator through the control of instrumented joysticks; the state of the manipulator could not affect the joysticks directly. In bilateral devices, not only is the slave manipulator actuated by electric motors (or hydraulic pumps), but the master station is also equipped with a motorized linkage. Information flows in both directions in these systems: from the sensors of the master to the actuators of the slave, and vice versa, from the sensors of the slave to the actuators of the master, so that forces exerted on the slave are reflected back to the master.

In earlier master-slave systems, all force and kinematic scaling was performed by analog electronic circuitry. Since digital computation was unavailable, the complexity of geometric transformations was averted by designing slaves with identical configurations to the masters. A result of building slaves that mimicked the kinematics of the master was the popularity of anthropomorphic linkages, both for the manipulator and the control station. One offshoot of anthropomorphic devices were the Handyman and Hardiman electrohydraulic "man-amplifiers" built by the General Electric Company in the 1960's [105]. The human interfaces for these devices were "worn" as exoskeletons by the operator. The Hardiman concept was particularly interesting because both master and slave were embodied as the same exoskeletal linkage. In principle, when wearing this device, the effort of the operator would be amplified by the actuators on the linkage. This "power assist" would enable the operator to produce very large forces and "lift" heavy loads. Ideally, from the perceptual point of view, the man-amplifier would have the effect of masking the inertial characteristics of massive external objects—in essence, physically simulating reduced mass properties.

The advent of laboratory interfaces (A/D and D/A conversion) for digital computers enabled telemanipulators to profit from the flexibility of programmable digital control algorithms. Aside from allowing a higher degree of autonomy on the part of the re-